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THEORY AND APPLICATION OF NON INVASIVE ULTRASONIC CROSS-CORRELATION FLOW METER IN HARSH ENVIRONMENT

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1. INTRODUCTION

The concept of the ultrasonic cross-correlation flow meter was first proposed in the early seventies. This technique demonstrated clear advantages over the more conventional transit-time method. However, cross-correlation meter was not commercialized due to the complicated data processing algorithm required and lack of understanding of underlying physical phenomena.

At the present time, enormous computing power of the PC and availability of commercial data acquisition and analysis software have eliminated the problem of data processing. On the other hand, better understanding of the physics involved in the interaction between ultrasonic waves and turbulence structures existing in a flowing fluid has resulted in development of a very accurate, reliable and affordable instrument.

The ultrasonic cross-correlation flow meter, known as CROSSFLOW™, has been used successfully in nuclear industry for non-invasive flow measurements at high temperaturesand high radiation fields. The meter has been installed for continuous on-line measurements, as well as used for periodic flow verification. The main advantage3 of the CROSSFLOW, from the point of view of flow measurements in harsh environment, is simplicity of transducer design, which allows installation in only a few minutes even under very poor access conditions. Data from on-line installations have confirmed very high meter reliability and insensitivity of the measurements to changes in external conditions. Experience gained from using the CROSSFLOW in nuclear industry points to ability of the meter to perform accurate and reliable flow measurements in other applications, including oil industry.

In this paper, fundamentals of the cross-correlation technique are discussed. Results of CROSSFLOW calibration, performance evaluation and examples of meter application are presented.

2. ADVANTAGES OF ULTRASONIC CROSS-CORRELATION TECHNIQUE

The design of the ultrasonic cross-correlation flow meter is based on the fact that when ultrasonic beam travels across a pipe in certain pipe cross-section "A" it is affected by random turbulent fluctuation of the flow parameters. After the received signal is processed a random signal Xa(t) - a signature of turbulence fluctuation in the flow in cross-section "A", can be obtained. If one transmits a second ultrasonic beam a certain distance L downstream of the first beam (in pipe cross-section "B"), it produces another random signal Xb(t). If distance L is small enough then approximately $X_a(t) = X_b(t + \tau^*)$ and value $Vm = L / \tau^*$ is interpreted as a measure of the flow velocity in the pipe [1]. (See Figure 1.)

This method has the following advantages over a more conventional transit time approach:

- Flow velocity is measured directly by measuring time of travel between two cross-sections. Typical magnitude of τ^* is of the order of 100 ms, in contrast to transit time meters, where typical difference in transit time is of the order of 1 μs.
- The result of measurement does not depend on speed of sound in the pipe material and in the fluid, which means the meter can work in a wide temperature range and for different materials;
- Direction of the ultrasonic beam is perpendicular to the pipe wall so the instrument is not very sensitive to installation and temperature changes during operation.
- The meter can operate for multiphase and mixed flows.
- Measured flow velocity is determined only by the axial velocity in the pipe and is not sensitive to the radial velocity component.

In spite of these advantages the cross-correlation meters were used only for specific applications such as water - sand or water -coal mixture, where application of other instruments was not feasible. Two major reasons prevented further development of the cross-correlation meters for pure liquids:
a) Calculation of the cross-correlation function was associated with bulky and expensive analog equipment. At the present time this problem is resolved by use of computers.
b) Physical interpretation of measured velocity in terms of the average flow velocity is not as transparent as for transit time meters, and the cross-correlation technique is considered as a purely empirical.

3. DEVELOPMENT OF THE NEW NON-INVASIVE ULTRASONIC CROSS-CORRELATION FLOW METER

One of the examples of successful application of this technique is associated with non-invasive ultrasonic cross-correlation flow meter for pure liquids, developed in earlier seventies by Canadian General Electric for Ontario Hydro [2]. The meter was calibrated at Ontario Hydro Research at the high temperature, high Reynolds number calibration facility. Calibration results and the use of the meter in Ontario Hydro nuclear power plants confirmed its high accuracy and its temperature stability [3]. However lack of quantitative understanding of the physics of meter operation, prevented optimization of the system and its application to a wide range of flow velocities and pipe diameters.

In 1995 Advanced Measurements and Analysis Group Inc. carried out rigorous analysis of the physics of ultrasonic cross-correlation flow measurements under Canadian Government grant-IRAP. Based on this analysis the following was achieved:

- Optimum magnitudes of the system parameters and data processing algorithm were related to the flow parameters such as pipe diameter, flow velocity and Reynolds number.
- Methodology of the flow meter calibration and of extrapolation of calibration results to the range of parameters outside of the calibration conditions was developed and tested.
- Numerical method based on k-e turbulence model was developed to calculate the ratio of the measured velocity to the average flow velocity for different pipe geometries, including bends and bend combinations. This method was used to extrapolate calibration results to high Reynolds Numbers for specific configurations of the pipe-lines. [4]
- Design of the acoustical system was optimized. Methodology was developed for adjusting acoustical parameters of the meter to acoustical parameters of the pipe and the fluid.

This work has resulted in a design of a significantly improved cross-correlation flow meter known as CROSSFLOW ™ . This meter has been installed for on-line high temperature flow measurements at a number of nuclear power plants in Canada and USA. The meter has also been used for short term flow measurements in number of facilities, including nuclear power plants in Canada, USA, Argentina, Romania, Brazil, France, Spain; water supply system; acid flow in chemical plant, etc.

The CROSSFLOW system includes a transducer frame, mounted on a pipe; ultrasonic probes (transmitters and receivers) mounted on the frame; multiplexer, capable to monitor up to eight pipes;

Signal Generating and Processing Unit; Personal Computer and Software (see Figure 1). The software controls the system, performs data acquisition, processing and analysis; records and stores data and can be easily adjusted to meet customer's needs.

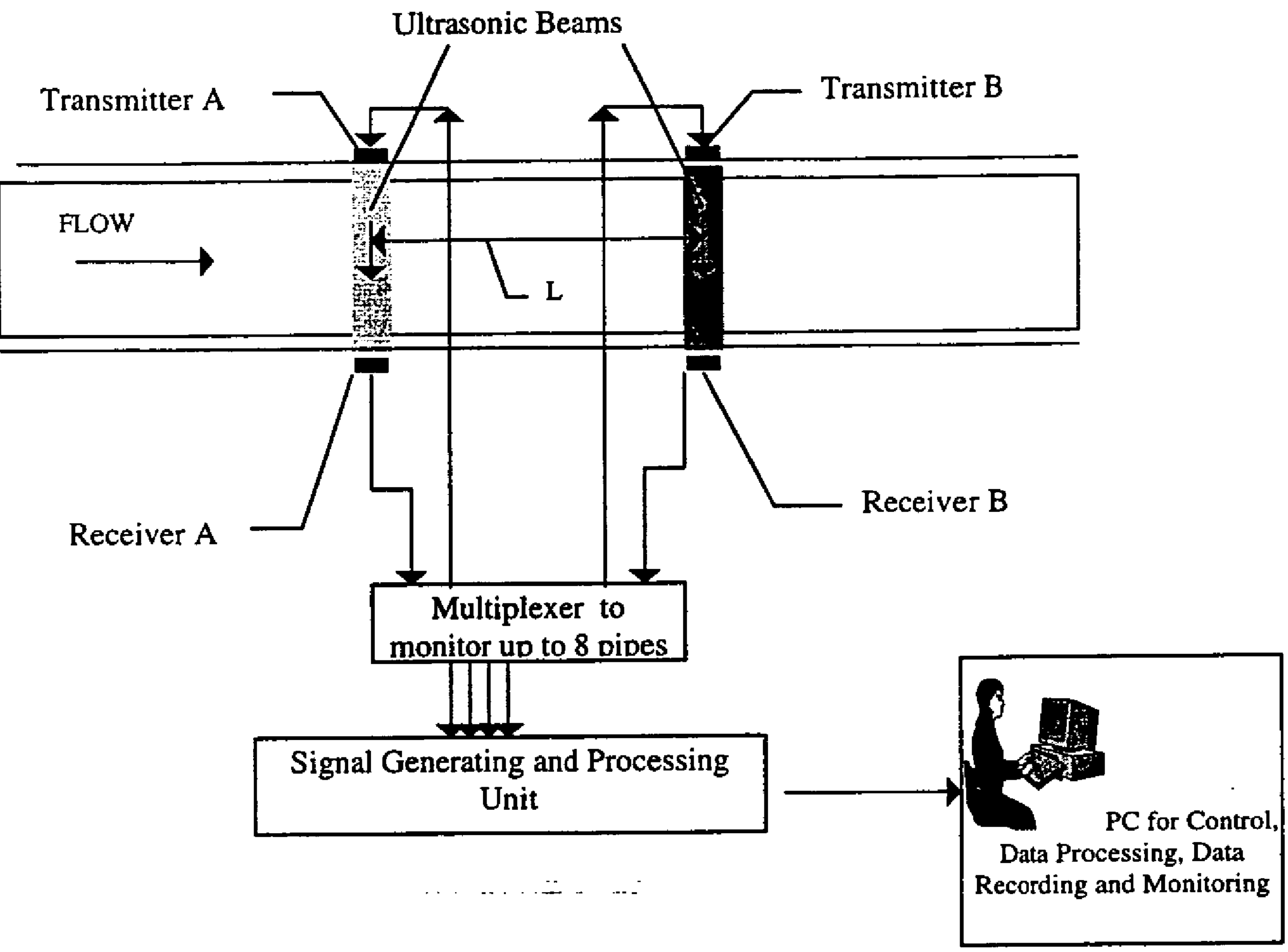

Figure 1. Ultrasonic Cross-Correlation non-invasive flow meter CROSSFLOW.

To enable the development of the improved meter, part of the project was dedicated to the theoretical analysis of the interaction between ultrasonic wave and turbulence in a pipe. This study resulted in a more accurate interpretation of the measured velocity in terms of the average velocity in a pipe. Quantitatively it gives the ratio of the average flow velocity Va to the measured velocity Vm as a function of Reynolds number. This relation was confirmed by calibration of the meter for Reynolds numbers up to 10 million. Good agreement with experiment allowed to use this relation for high temperature measurements with Reynolds Number 20 - 30 millions, which is much higher then calibration facility can provide.

4. THEORY OF CROSS-CORRELATION ULTRASONIC FLOW METER. ULTRASONIC WAVE – TURBULENCE INTERACTION.

4.1 Measured velocity - Vm

Fundamental problem of the theory of ultrasonic cross-correlation flow measurement is relation of measured velocity Vm to the averaged flow velocity Va.

Measured flow velocity

$$Vm = L / \tau^* \qquad (1)$$

is determined by the constant distance between ukltrasonic beams - L and by time delay between two signals Xa(t) and Xb(t). The time delay τ^* is calculated as a position of maximum of the cross-correlation function R_{ab}

$$R_{ab} = \int X_a(t) X_b(t+\tau) dt \qquad (2)$$

Signals Xa(t) and Xb(t) are the result of the effect of turbulence on the ultrasonic beam in the pipe. Usually it is assumed that Vm is an average of the velocity distribution in a pipe along the ultrasonic beam, directed along pipe diameter. This assumption probably is correct if signals Xa(t) and Xb(t) are produced by a turbulent feature, uniformly distributed along pipe diameter, such as concentration of passive second phase.

In more general case the measured velocity Vm is related to velocity distribution in the pipe as follows:

$$Vm = \int_0^D U_x(r) \cdot F(r) dr \qquad (3)$$

where D is pipe diameter, $U_x(r)$ - time averaged axial flow velocity and weight function F(r) depends on the nature of the signals Xa(t) and Xb(t). Relation between measured velocity Vm and velocity distribution in the pipe depends on the following major factors:

a) the nature of perturbation of the ultrasonic wave - perturbation due to fluctuation of temperature or velocity or concentration of a second phase in the flow, etc.

b) on the type of processing of the received signal - amplitude or phase demodulation of the ultrasonic wave or filtering, saturation, amplification of the demodulated signal etc.

Therefore interpretation of measured velocity Vm requires more deep quantitative analysis of the process of ultrasonic wave perturbation by the flow.

4.2 Effect of turbulence in a pipe on ultrasonic wave in a pure liquid

Normally the amplitude of velocity and pressure fluctuations in ultrasonic wave is very small, and flow velocity field (including turbulent velocity fluctuation) is not effected by ultrasound.

Total velocity field in the flow under ultrasonic irradiation U*(r,t) can be described as a superposition of undisturbed turbulent velocity field Uo (r,t) and disturbed ultrasonic wave U:

$$U^{*} = Uo + U \qquad (4)$$

Ultrasonic wave in a turbulent flow can be described approximately by linear wave equation with coefficients, which are functions of time and coordinates and are determined by known turbulent velocity distribution Uo and its derivatives. [1] Maximum frequency of turbulent flow pulsation in a pipe is estimated as Va / λ_k where λ_k is Kolmogorov scale [5] . This frequency for typical pipe flow is order of 1 KHz and is much smaller then typical frequency of the ultrasonic wave. Then ultrasonic wave can be presented in the form of high frequency periodic function with low frequency disturbed amplitude A and phase φ:

$$U(r,t) = A(r,t)\cos(\omega \cdot t + k \cdot r + \varphi) \qquad (6)$$

Analysis of the wave equation shows that in equation (6) the amplitude A is determined by solution of differential equation. Coefficient in this equation are determined by turbulent velocity field Uo.. In contrast, phase φ has a simple physical interpretation. If an ultrasonic wave is induced by the ultrasonic source at r = 0 then at r = D

$$\varphi(t) = \varphi_0 + (\omega / C^2)\int_0^D U_{0r}(r,t)dr \qquad (7)$$

where Uor is radial component of the velocity Uo (projection of the velocity vector Uo on the direction of the ultrasonic beam), C is speed of sound in the liquid, φ_0- constant.

Thus, if signals Xa (t) and Xb(t) represent phase change of the ultrasonic wave then they are determined by expression (7) and they can be expressed in terms of turbulent parameters of the flow..

4.3 Estimation of the measured velocity for a straight pipe.

The integral in equation (7) is approximately proportional to the product of intensity of turbulent velocity pulsation u_t and scale of turbulence λ_t and therefore is proportional to the turbulent viscosity μ_t [5].

$$\int_0^D U_{0r}(r,t)dr \approx u_t \cdot \lambda_t \approx \mu_t \qquad (8)$$

Parameter μ_t is widely used in many turbulence models and can be calculated for different pipe configurations. Typical shape of μ_t is shown in Figure 2. This shape, according Nikuradze [6] is independent on Reynolds Number.

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[1] Derivation of the wave equation and more detale analysis of the problem will be published separately.

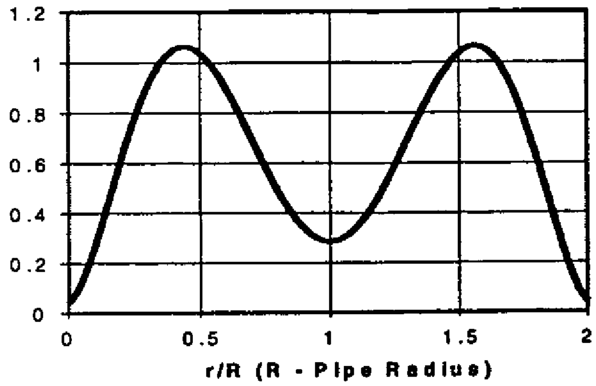

Figure 2. Qualitative Distribution of Effective Turbulent Viscosity in a pipe.

Using Nikuradze data on velocity and turbulent viscosity distribution in a pipe [6] and equation (8), one can obtain dependence of the measured velocity Vm on the average flow velocity Va in the form:

Va = Vm C(Re)

where Re is Reynolds Number. Function C(Re) is known as the Velocity Factor and is shown in Figure 3.

Equations (7) and (8) also used to optimize characteristics of the flow meter and signal processin algorithm. For example distance between probes, frequency range for signals Xa(t) and Xb(t), time of correlation and others depending on pipe's diameter, flow velocity and Reynolds Number.

5. CALIBRATION OF ULTRASONIC CROSS-CORRELATION FLOW METER FOR STRAIGHT PIPS

5.1 Calibration methodology

The curve presented in Figure 3 was obtained assuming a perfect correlation between signals Xa and Xb . This assumption means that

a) distance between probes A and B is smaller then "distance of life" of turbulence structures in the flow and

b) signals Xa and Xb include sufficiently wide range of turbulent spectrum in the pipe.

To satisfy these conditions the characteristics of the flow meter, have to be adjusted to the pipe diameter, flow velocity and Reynolds number. Then calibration curve will be function of only Reynolds Number irrespective of pipe's diameter and flow velocity.

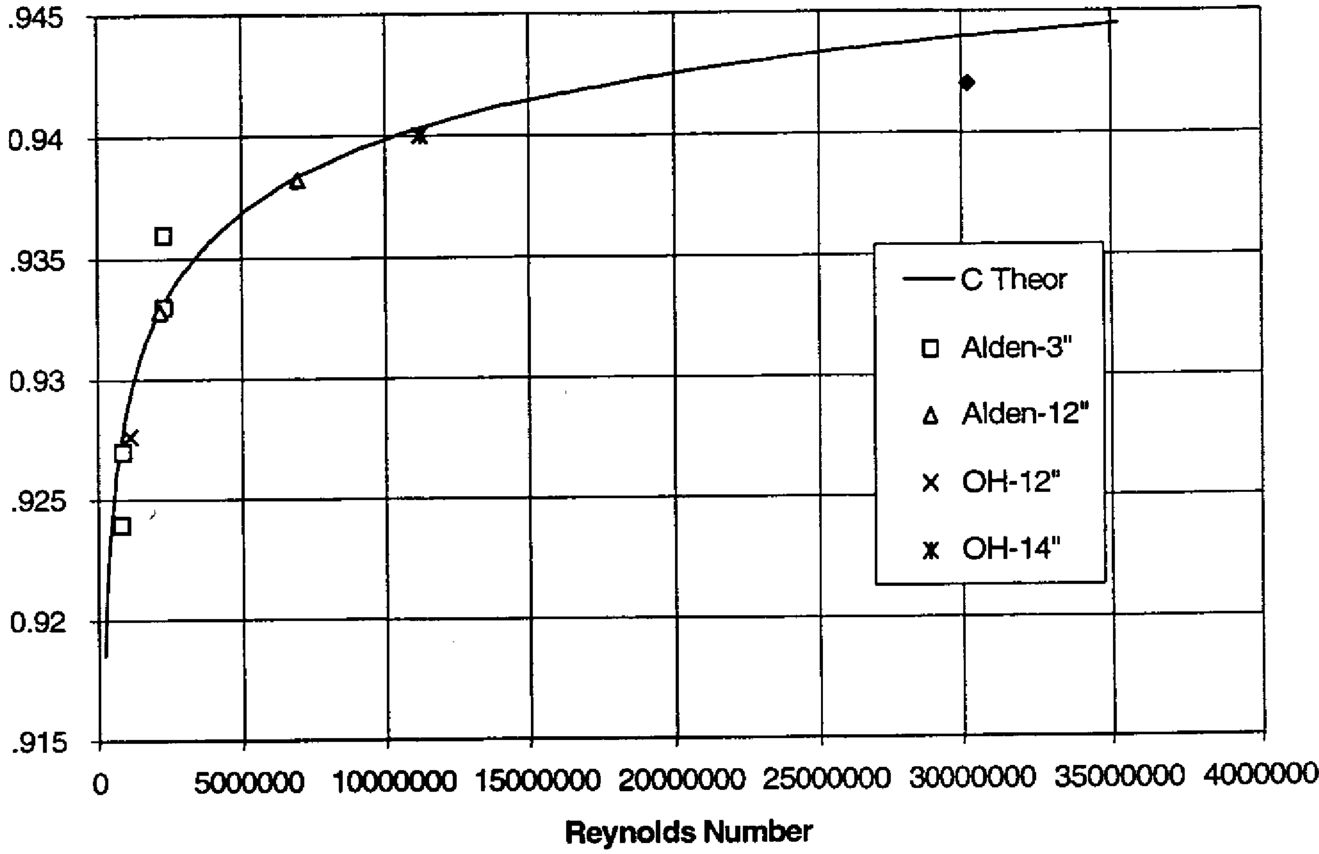

Figure 3. Velocity Factor C (Re). Theory and Calibration. Point ◆ - comparison with calibrated venturi nozzle in nuclear power plant.

5.2 Calibration results

In Figure 3 the curve for the calibration coefficient C is presented together with experimental data. Experiments were carried out in Alden Research Laboratory (USA) and in Ontario Hydro Research Laboratory (Canada) with high temperature flow. Measurements were performed on plastic pipes and carbon steel pipes with diameters from 2 inches (5 cm) to 16 inches (40 cm) in the range of Reynolds numbers from 700,000 to 10,000,000. Data for high temperature flow (Reynolds number from 7,000,000 to 10,000,000) were obtained in Ontario Hydro Research Laboratory. Special facility in this laboratory allowd to get flow temperature up to 200 C. Flow was measured by the venturi nozzle with accuracy 0.5% [3]. In Alden Research Laboratory flow was mea by weigh tank with accuracy 0.25%. Maximum Reynolds Number was around 5 millions.

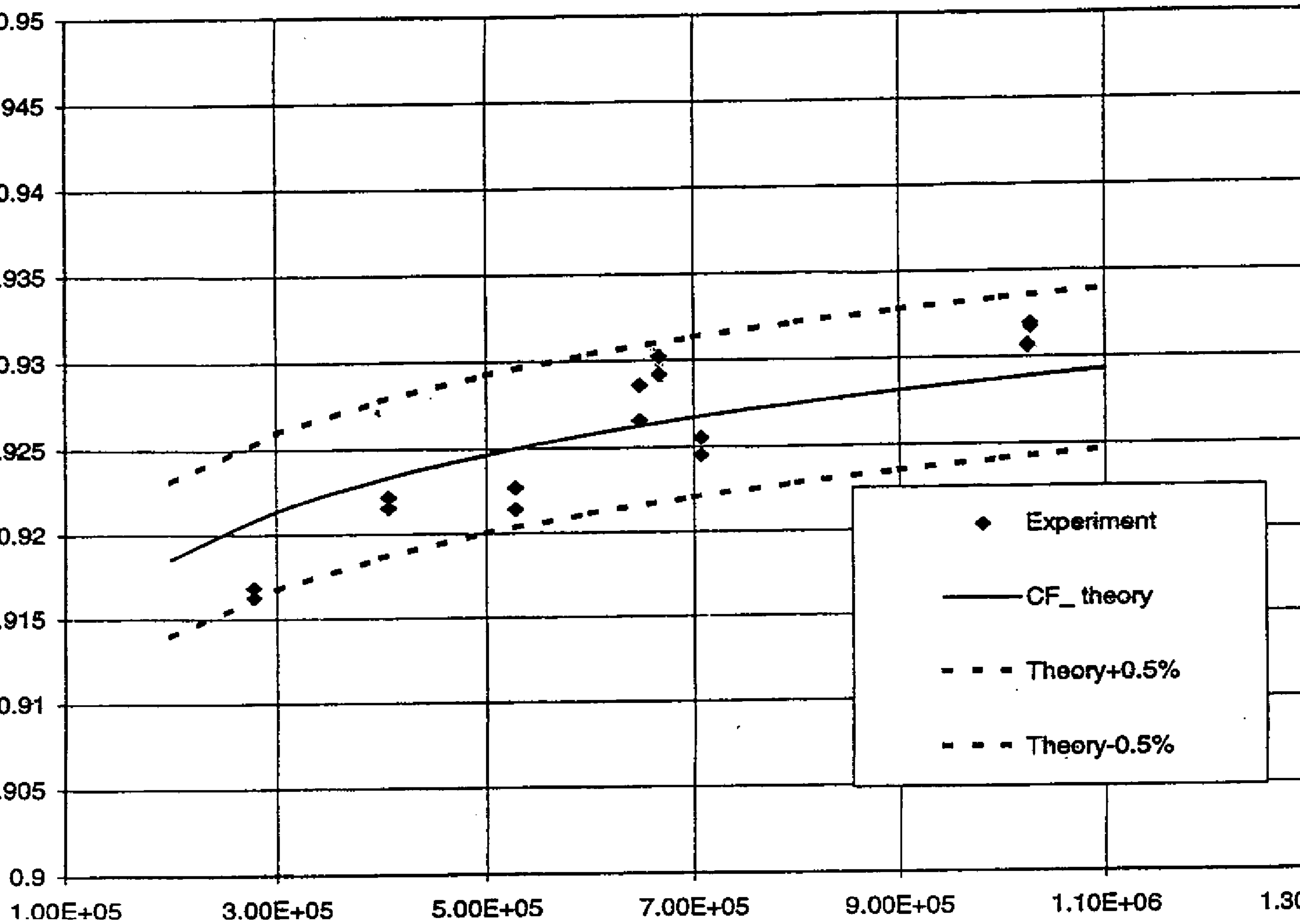

Figure 4. CROSSFLOW Calibration for 300 000 <Re< 1 000 000

Calibration for Reynolds numbers 300 000 < Re < 1000000 was carried out in Ontario Hydro Flow Test Laboratory on 12 inch pipe. Results are presented in Figure 4. In this figure all experimental points are within ± 0.5% interval from the theoretical curve. The flow in Ontario Hydro Flow Test Laboratory is produced by head tank and is measured by weigh tank. Accuracy of flow measurements using weigh tank is 0.5%. Maximum Reynolds number is 1 million.

The results of calibration shown in Figures 3 and 4 demonstrate that the difference between the theoretical curve and experimental data is within the accuracy of the experiment. Statistical analysis of the data shows that in the range of Reynolds Number from 0.3million to 10 million the curve gives calibration coefficient C with uncertainty better then 0.05%.

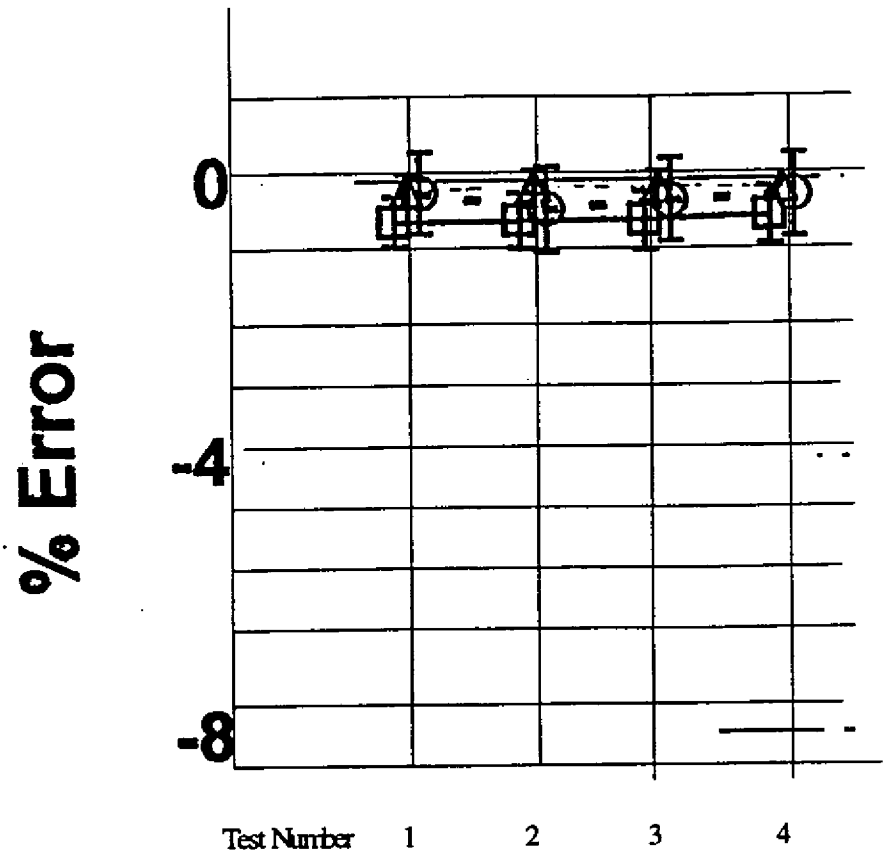

Figure 5. CROSSFLOW Reproducibility (see text for details)

5.3 CROSSFLOW Reproducibility

Results of the meter's reproducibility are shown in Figure 5. The tests were carried out in National Institute of Standards and Technology in Washington on 10 inch stainless steel pipe. The flow was provided by the pump. CROSSFLOW measurements were compared with weigh tank measurements. The error in the graph is calculated as a difference between weigh tank data and flow measurement using instrument under test. Test number 1 is a normal flow measurement. Test number 2 is a measurement after the pump was re-started. For test number 3 the ultrasonic probes were re-mounted on the frame. For test number 4 the frame with ultrasonic probes was re-mounted on the pipe. The three meters under test are: electro- magnetic meter, previously calibrated on the same position on the pipe - O; Ultrasonic transit time flow meter with four ultrasonic paths, installed invasively - Δ; CROSSFLOW - . The results demonstrate reproducibility around 0.2%.

6. CROSSFLOW APPLICATION IN HARSH ENVIRONMENT

One of the applications of the non invasive cross-correlation flow meter CROSSFLOW for high temperature flows is Feedwater flow measurement in nuclear power plants. Typical parameters of this flow are: pipe diameters 12– 30 inches, water temperature approximately 230 C°, pipe material- carbon steel, pipe wall thickness 1 – 2 inches, Reynolds number up to 30,000,000,

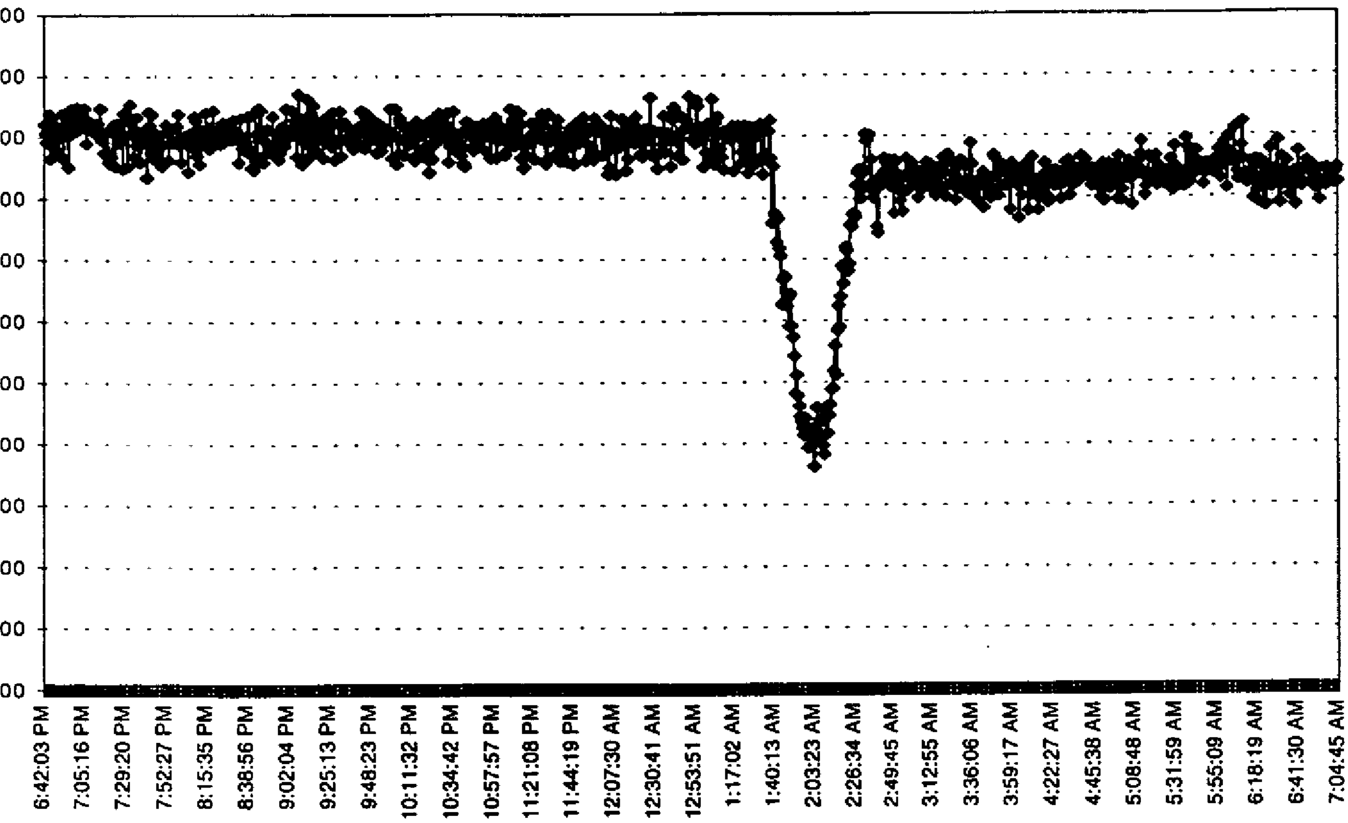

Figure 6. Typical Flow Measurement. Pipe temperature 230C. Flow change from 100% to 90% to 99% of normal value.

which is normally not achievable in a laboratory environment. Depending on particular case the meter installation is carried out under high temperature up to 45-50C° ; high radiation field and difficult access to the pipes. The pipe temperature itself during installation and operation is around 200C. Surrounding temperature during operation is 45-50C°

Other important application of the CROSSFLOW is reactor coolant flow measurement with flow temperature approximately 300 C° and pipe diameters 2 – 20 inches. Specifics of this measurement are:

a) High environmental temperature - 300 C°, which practically exclude possibility of cooling of the ultrasonic probes and use of rubber coupling.

b) High radiation fields, which reduces limit for time of installation to a 10 - 15 minutes.

c) Excess to the transducer is impossible during plant operation, which requires high reliability of the system without maintenance service during 1- 2 years.

Typical result of the flow measurement is shown in Figure 6. In this application the plant power is proportional to the flow. During time interval shown on the graph the plant power changes from 100% to 90% and to 99% of the normal value. From the graph it is clear that the meter's resolution is high enough to resolve significantly smaller flow change then 1%.

7. CONCLUSION

Present stage of the ultrasonic cross-correlation technology allows to provide flow measurements with accuracy around 0.2%. The measurements can be performed in a wide range of pipe diameters, pipe materials, pipe wall thickness, liquides and flow velocities. The only limitations of the technology are:

a) the pipe and the flow have to be transparent to the ultrasonic wave;
b) The ultrasonic wave has to be effected by the random fluctuation of the flow parameters. In case of pure liquids it is a turbulent pulsation of the flow velocity. In case of multiphase liquids it could be fluctuations of concentration of the second phase.

The technology allows providing non-invasive flow measurements in harsh environment and in situations were installation is complicated by difficult access to the pipe or by other specific requirements.

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